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A COMPARISON OF THE EFFECTS OF SPECIMEN THICKNESS AND
SUBCRITICAL CRACK GROWTH ON SEVERAL NONLINEAR
FRACTURE TOUGHNESS PARAMETERS,

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ABSTRACT

Theoretical and experimental comparisons have been made between several nonlinear fracture toughness methods including J_{Ic} (J integral method), G_{COD} (COD method) and \tilde{G}_{Ic} (nonlinear energy method). Three series of compact tension specimens of 7075-T651, 2124-T851 and Ti-6Al-4V were tested. Five fracture toughness tests, at thicknesses above and below the minimum value for plane strain fracture, were conducted in each series, and toughness values were compared at: (a) the onset of stable crack growth and (b) at the onset of unstable fracture. It was found that when the critical point was the onset of stable crack growth J_{Ic} , \tilde{G}_{Ic} and \bar{G}_{Ic} (linear toughness) were independent of specimen thickness. When the critical point was the onset of unstable fracture all three toughness values increased with decreasing thickness, with $\tilde{G}_{Ic} > J_{Ic} > \bar{G}_{Ic}$. The G_{COD} values were much higher than the others in all cases.

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INTRODUCTION

Widespread acceptance of linear elastic fracture mechanics concepts in recent years has resulted in the development of new structural alloys having fracture toughnesses significantly higher than the older high-strength, low-toughness alloys, while maintaining yield strengths at previous levels. However, in fracture toughness testing these materials exhibit considerable nonlinear deformation, due to crack-tip plasticity and subcritical crack growth, prior to unstable fracture. To meet the ASTM requirement for plane strain fracture toughness testing, E399, the minimum specimen thicknesses for many of these materials are too large for economical testing and also much greater than most structural applications.

Several approaches to obtaining a suitable fracture toughness test method have been proposed for materials which exhibit considerable nonlinear response prior to unstable fracture. The first approach, suggested by Irwin, et al. [1,2], involved determining the size of the crack-tip plastic zone and calculating the linear fracture toughness as though the crack size had increased by an amount equal to the plastic zone size. In cases where extensive crack-tip plastic deformation occurs without subcritical crack growth, Wells [3] proposed that the material will fail under a condition that leads to a particular amount of deformation at the crack tip,

a quantitative measure of which can be obtained from the crack-tip opening displacement. Rice [4,5] introduced a line energy integral (J integral), which includes nonlinear deformation in the vicinity of the crack-tip. The J integral was initially treated as a failure criterion by Begley and Landes [6,7], and is currently being evaluated as a nonlinear fracture toughness parameter in a round-robin test program. Another nonlinear fracture mechanics method, called the nonlinear energy method, has also been proposed [8,9]. This method, which is based on a general definition of fracture toughness, permits the straightforward determination of a nonlinear fracture toughness parameter, \tilde{G}_c or \tilde{G}_{Ic} , from the load-displacement record of a single fracture toughness test. The nonlinear toughness parameter is defined as the energy rate in a semibrittle material and is given by

$$\tilde{G}_c = \tilde{C} \bar{G}_c \quad (1)$$

where \tilde{C} is a measure of the curvature of the load-displacement record and \bar{G}_c is the linear toughness. Since \tilde{C} approaches unity as the load-displacement record approaches a straight line, it is clear that \tilde{G}_c approaches the linear fracture toughness when brittle materials are tested.

All of the nonlinear fracture mechanics methods, though different in their approaches, propose fracture toughness parameters similar to the linear fracture toughness. In this

paper the analytical bases for these approaches have been outlined and the methods of obtaining the toughness values from experimental data have been discussed in detail. Experimental comparisons among the nonlinear energy (\tilde{G}_{Ic}), the J integral (J_{Ic}), and the crack-opening displacement (G_{COD}) toughness values have been made and their variation with specimen thicknesses greater and less than the thickness required by ASTM E399 is presented in this report. The toughness values were determined at two critical points, (a) the initiation of subcritical crack growth and (b) the onset of unstable fracture. The materials used for these tests include two aluminum alloys 7075-T651 and 2124-T851 and a titanium alloy Ti-6Al-4V in the β forged condition.

THE DEVELOPMENT OF VARIOUS NONLINEAR METHODS

The Crack-Opening Displacement Method. Wells [3] assumed that, when crack-tip yielding occurs, there is a close relationship between the energy released and the energy absorbed during an increment of crack growth after separation of the crack surfaces through a critical displacement, δ_c . When the crack-tip plastic zone is small compared to the crack length, this relationship can be obtained using a quasielastic approach (the strip yield model). A relationship between δ , the nominal stress (σ), the yield strength (σ_{ys}), and the crack length ($2a$) can be obtained [10] from the strip yield model as

$$\begin{aligned}\delta &= \frac{8\sigma_{ys}a}{\pi E} \ln \sec\left(\frac{\pi\sigma}{2\sigma_{ys}}\right) \\ &= \frac{8\sigma_{ys}a}{\pi E} \left\{ \frac{1}{2} \left(\frac{\pi}{2} \frac{\sigma}{\sigma_{ys}} \right)^2 + \frac{1}{12} \left(\frac{\pi}{2} \frac{\sigma}{\sigma_{ys}} \right)^4 + \frac{1}{45} \left(\frac{\pi}{2} \frac{\sigma}{\sigma_{ys}} \right)^6 + \dots \right\}. \quad (2)\end{aligned}$$

Considering only the first term in Eq.(2) leads to

$$\delta = \frac{\pi\sigma^2 a}{E\sigma_{ys}}. \quad (3)$$

From Griffith's analysis of an infinite sheet containing a crack of length $2a$, it has been shown that

$$G = \frac{\pi\sigma^2 a}{E}, \quad (4)$$

which is substituted into Eq.(3) to yield

$$G_{COD} = \sigma_{ys} \delta_c. \quad (5)$$

It is clear from this development that considerable approximations are employed in order to obtain Eq.(5). For example, the suitability of the strip yield model for this analysis has not been verified in a general manner and may be completely inappropriate. There is also no general agreement as to how the crack-opening displacement can be accurately measured. Additional inaccuracies are also introduced by the use of Eq.(5) for both plane stress and plane strain conditions [11]. Moreover, the COD measurement is not reliable once subcritical crack growth is initiated, and the COD criterion is not applicable in such cases.

The J Integral Method. In an elastic medium the J integral [4,5], defined as

$$J = \int_{\Gamma} \left(\Sigma dy - \vec{T} \cdot \frac{\partial \vec{u}}{\partial x} ds \right), \quad (6)$$

where Σ is the elastic strain energy density, \vec{T} is the surface traction vector and \vec{u} is the displacement vector, has been shown to be a path-independent energy line integral. The contour Γ begins on one crack surface and ends on the other so as to encompass the crack tip, but because of its path independence, it can otherwise be arbitrarily located.

If the global elastic potential energy for a nonlinear elastic material is defined as

$$P = \bar{U} - W, \quad (7)$$

where \bar{U} is the total strain energy and W is the work done, it has been shown that

$$J = - \frac{\partial P}{\partial c} . \quad (8)$$

The J integral was defined for a linear or nonlinear elastic medium. When the loading is monotonic and proportional, the deformation theory of plasticity is equivalent to the nonlinear elastic analysis of deformation. Hence, small-scale plastic crack-tip deformation can be approximated by a deformation theory of plasticity. However, the J integral is a derivative of the potential energy with respect to crack length, Eq.(8). For a nonlinear elastic body J may be interpreted as the rate of change of potential energy with crack extension, similar to G_c . But, for a general elastic-plastic problem, there is always crack-tip unloading with crack growth and plastic deformation is irreversible. Therefore, J cannot be interpreted as an energy change rate with crack extension and the deformation plasticity theory is not applicable. It can be considered as an energy comparison of two similar bodies with slightly different crack sizes loaded in the same manner, in which case the deformation theory may be appropriate; but this energy comparison is not equivalent to the rate of energy change in the process of crack extension. Hence, the J integral is essentially a nonlinear elastic energy release rate criterion used as an approximate criterion for an

elastic-plastic material. Further, as in the case of the COD method, the J integral approach is not applicable when there is subcritical crack growth.

The Nonlinear Energy Method. From a global energy balance consideration during slow crack growth in a cracked body, the nonlinear energy toughness, \tilde{G}_c , has been defined [9] as

$$\tilde{G}_c = \frac{\partial}{\partial c}(W - U' - U'')_{\text{crit}} = \frac{\partial \Gamma}{\partial c} \quad (9)$$

in which

W = the external work,

U' = elastic strain energy,

U'' = plastic strain energy, and

Γ = fracture surface energy.

This definition is valid regardless of whether the material exhibits a linear or nonlinear response during deformation. From this general definition, an expression for fracture toughness has been obtained, which can be easily evaluated from conventional fracture toughness test results.

The load-displacement record obtained from a fracture toughness test of a material exhibiting crack-tip plasticity is represented generically in Fig. 1. This curve can be represented by a three-parameter Ramberg-Osgood relation as

$$v = \frac{F}{M} + k \left(\frac{F}{M} \right)^n \quad (10)$$

in which

v = displacement

F = load

M = initial specimen modulus

and k and n are constants for a given test curve. The internal energy stored by the specimens, $U = U' + U''$, prior to crack initiation can be obtained from Eq.(10) as

$$U = Fv - \int_0^F v dF$$

$$= \frac{F^2}{2M} \left[1 + \frac{2nk}{n+1} \left(\frac{F}{M} \right)^{n-1} \right] . \quad (11)$$

Under a constant load condition of crack-growth, $\frac{\partial W}{\partial c}$ and $\frac{\partial U}{\partial c}$ can be obtained as

$$\frac{\partial W}{\partial c} = F \frac{\partial v}{\partial c} = \left\{ 1 + nk \left(\frac{F}{M} \right)^{n-1} \right\} F^2 \frac{\partial (1/M)}{\partial c} \quad (12)$$

and

$$\frac{\partial U}{\partial c} = \frac{F^2}{2} \left[1 + \frac{2n^2 k}{n+1} \left(\frac{F}{M} \right)^{n-1} \right] \frac{\partial (1/M)}{\partial c} , \quad (13)$$

from which it is seen that

$$\begin{aligned} \tilde{G}_{Ic} &= \frac{\partial W}{\partial c} - \frac{\partial U}{\partial c} = \left[1 + \frac{2nk}{n+1} \left(\frac{F}{M} \right)^{n-1} \right] F^2 \frac{\partial (1/M)}{\partial c} \\ &= \tilde{C} \bar{G}_{Ic} . \end{aligned} \quad (14)$$

In Eq. (14)

$$\tilde{C} = \left[1 + \frac{2nk}{n+1} \left(\frac{F}{M} \right)^{n-1} \right]$$

and

$$\bar{G}_{Ic} = \frac{K_{Ic}^2 (1-\nu^2)}{E} = \frac{F^2}{2} \frac{\partial (1/M)}{\partial c}$$

is the linear fracture toughness under plane strain conditions.

EXPERIMENTAL PROCEDURE

Experimental comparisons between \tilde{G}_{Ic} , J_{Ic} and G_{COD} as failure criteria were made by fracture toughness testing of three sets of compact tension specimens prepared from plates of 7075-T651 and 2124-T851 aluminum alloys and Ti-6Al-4V alloy in the β -forged condition. At least five specimens were tested in each set. The specimens conformed with the ASTM E399 requirements, with $w = 3.0$ in., except for specimen thickness. In each set were included specimens having thicknesses both above and well below the minimum requirement for plane strain fracture, $B \geq 2.5(K_{Ic}/\sigma_{ys})^2$. The tests were conducted on an MTS servohydraulic system operated in load control.

The specimens that had thicknesses lower than the minimum thickness required for plane strain fracture showed evidence of significant subcritical crack growth. Although subcritical crack growth was not usually observed directly, it was inferred from sudden changes in slope of the load-displacement curves. Most of the nonlinearity of the curves occurred after the onset of subcritical crack growth. Two critical points were identified for these tests: (a) the onset of subcritical crack growth, and (b) the initiation of unstable fracture, which corresponded to the maximum load. From an engineering point of view the second critical point

(unstable fracture) is more important than the first. However, the analytical bases for most of the nonlinear methods are appropriate only to the onset of subcritical crack growth. In order to obtain a better appreciation of several of the nonlinear toughness values under different amounts of nonlinear behavior, several of them were determined from the load-displacement record at point (a) as well as at point (b). For reference purposes the linear toughness value \bar{G}_{Ic} was also calculated based on the corresponding load. These values coincided with the G_{Ic} value when the minimum thickness requirement was satisfied.

Nonlinear Energy Method. The procedure for evaluating \tilde{G}_{Ic} is given in Ref.[12]. The relation, $\tilde{G}_{Ic} = \tilde{C}\bar{G}_{Ic}$, is applicable for plane strain as well as plane stress conditions. The quantity \tilde{C} is obtained by drawing the initial tangent and two reduced modulus lines to the load-displacement curve, one of which passes through the critical point, Fig. 1. At the two intersection points of the secant lines with the load-displacement record the following conditions are satisfied

$$\begin{aligned} v_1 &= \frac{F_1}{\alpha_1 M} = \frac{F_1}{M} + k \left(\frac{F_1}{M} \right)^n, \\ v_2 &= \frac{F_2}{\alpha_2 M} = \frac{F_2}{M} + k \left(\frac{F_2}{M} \right)^n, \end{aligned} \quad (15)$$

from which

$$\frac{1-\alpha_1}{\alpha_1} = k \left(\frac{F_1}{M} \right)^{n-1}, \quad (16)$$

$$\frac{1-\alpha_2}{\alpha_2} = k \left(\frac{F_2}{M} \right)^{n-1}.$$

By eliminating k from Eq.(16), it is seen that

$$n = \frac{1 + \ln[\alpha_2(1-\alpha_1)/\alpha_1(1-\alpha_2)]}{\ln(F_1/F_2)}, \quad (17)$$

and the expression for \tilde{C} can be written

$$\tilde{C} = 1 + \frac{2n(1-\alpha_1)}{\alpha_1(n+1)} \left(\frac{F_c}{F_1} \right)^{n-1} = 1 + \frac{2n(1-\alpha_2)}{\alpha_2(n+1)} \left(\frac{F_c}{F_2} \right)^{n-1}. \quad (18)$$

Since $F_c = F_2$, Eq.(18) assumes the simplified form

$$\tilde{C} = 1 + \frac{2n(1-\alpha_2)}{\alpha_2(n+1)}. \quad (19)$$

Thus \tilde{C} can be determined for any load-displacement record by evaluating the parameters α_1, α_2, F_1 and $F_2 = F_c$. Since \tilde{C} is not dependent on M , but only on α_1, α_2 and n , the load-clip gauge displacement curve can be used for the determination of \tilde{C} ; i.e., it is not necessary to obtain the load-point displacement.

COD Method. In principle, the calculation of G_{COD} from the COD value is straightforward because of the simplified relation $G_{COD} = \sigma_{ys} \delta_c$. However, the technique for determining

δ_c is not well established. The most widely used approach is to calculate it from clip gauge displacement measurements. Dover[13] assumed that the specimen deformation can be represented by a rotation about some point $r(w-a)$ ahead of the crack, Fig. 2. Hence the ratio of the clip gauge reading, V_g , and δ is given by

$$\frac{V_g}{\delta} = 1 + \frac{a+z}{r(w-a)} \quad (20)$$

The viewpoint is generally held that r remains constant above certain large values of displacement. However, there is no general agreement as to the exact value of r . Another method of determining r for compact tension specimens was developed by Egan[14] from a finite element analysis. In the present investigation the Egan approach for determining r was followed.

J Integral Method. The procedure initially followed by Begley and Landes for evaluation of J_{Ic} [6,7] involved a nonlinear compliance approach using several specimens of different crack lengths. However, Rice, Paris and Merkle(15) stipulated that, for deeply notched specimens, J_{Ic} can be obtained as

$$J_{Ic} = \frac{2A}{B(w-a)} \quad (21)$$

where A is the area under the load-load point displacement curve up to the critical point and B is the thickness. From the Ramberg-Osgood representation of the load-displacement record, the area under the load-clip gauge displacement curve,

A_g , can be obtained by integration as

$$A_g = \frac{\tilde{C}F_c^2}{2M} \quad (22)$$

The value of M is dependent on the point where the displacement is measured. Hence, the clip gauge displacement reading, V_g , gives a lower value of M than the load point displacement. J_{Ic} should be determined from the area under the load-load point displacement curve in the form

$$A = \frac{\tilde{C}F^2}{2M} \times \frac{V_\ell}{V_g} \quad (23)$$

From the procedure used for determining δ , it can be seen that

$$\frac{V_\ell}{V_g} = \frac{a+r(w-a)}{z+a+r(w-a)} \quad (24)$$

RESULTS AND DISCUSSION

The linear fracture toughness (\bar{G}_{Ic}), the nonlinear energy toughness (\tilde{G}_{Ic}), J_{Ic} , and G_{COD} were evaluated for each specimen from a single load-displacement record. These quantities were obtained at two critical points -- the onset of subcritical crack growth and the initiation of unstable crack propagation (maximum load). This procedure facilitated comparisons among the different fracture toughness parameters as a function of thickness for the alloys 7075-T651, 2124-T851 and Ti-6Al-4V in the β forged condition.

The test results of the relatively brittle 7075-T651 alloy are shown in Fig. 3a and b. The toughness values corresponding to the 0.063 in. thickness were obtained from center-cracked sheet specimens. All of the other results were determined from tests on compact tension specimens. When the maximum load was selected as the critical point, all of the toughness parameters increased markedly with decreasing specimen thicknesses as is seen in Fig. 3a. \bar{G}_{Ic} , \tilde{G}_{Ic} and J_{Ic} displayed a regular variation with changes in thickness, with \tilde{G}_{Ic} consistently higher than J_{Ic} and J_{Ic} higher than \bar{G}_{Ic} . The differences among the three toughness parameters decreased with increasing thicknesses. When the thicknesses satisfied the ASTM requirement, the toughness values almost coincided, as would be expected from the analytical bases of the methods.

As compared to these three toughness parameters, the G_{COD} values were significantly larger at all thicknesses, and they varied with specimen thickness in an irregular manner.

When the onset of subcritical crack growth was chosen as the critical point, the \bar{G}_{Ic} , \tilde{G}_{Ic} and J_{Ic} toughness values were seen to be independent of thickness changes, and were very close to one another, as seen in Fig. 3b. For all thicknesses except 0.5 in., the J_{Ic} values were smaller than \bar{G}_{Ic} . As in Fig. 3b, the G_{COD} values were much higher than the other three and varied irregularly with the specimen thickness.

In Fig. 3a and 3b there was no significant change in \bar{G}_{Ic} and \tilde{G}_{Ic} values when the specimen geometry was changed from compact tension to center-cracked sheets, since all of the points fit into a smooth curve. This behavior demonstrates the lack of dependency of \tilde{G}_{Ic} and \bar{G}_{Ic} on specimen geometry.

At thickness values above that required by ASTM E399, $G_{Ic} = K_{Ic}^2/E = \bar{G}_{Ic}$ and is expected to remain independent of additional increases in specimen thickness. In 7075-T651 only the specimen with thickness 0.5in. met the ASTM requirement.

As currently formulated[16], J_{Ic} is claimed to be constant to a considerably lower thickness ($50 J_{Ic}/\sigma_{ys}$) than

that required by the linear ASTM method. It can be seen from Fig. 3b that J_{Ic} evaluated at the onset of subcritical crack growth does exhibit geometry independence down to the thinnest specimen tested. It is noted that for these tests practically no nonlinearity in the load-displacement record occurred prior to the onset of subcritical cracking. However, when the maximum load was taken as the critical point, J_{Ic} increased substantially with decreasing thickness.

The thickness dependency of toughness values for the more ductile 2124-T851 alloy, Fig. 4a and b, was similar to that for 7075-T651. However, the toughness values exhibited more scatter than for the 7075 alloy. The experimental scatter in all of these results would certainly be reduced if at least three specimens are tested at each thickness, as recommended in ASTM E399. The 2124 alloy specimens with thickness greater than 1.2 in. satisfied the thickness requirement and accordingly gave toughness values independent of thickness in this region. The minimum thickness for which J_{Ic} was supposed to remain constant, $50J_{Ic}/\sigma_{ys}$ was approximately 0.1 in. for this alloy when the maximum load is taken as the critical load, Fig. 4a. But as in the case of 7075-T651, the J_{Ic} value increases with decreasing thickness below 1.2 in. When the onset of subcritical crack growth is taken as the critical point, \bar{G}_{Ic} , \tilde{G}_{Ic} and J_{Ic} were essentially independent of specimen thickness. As before, the values for G_{COD} were much

higher than the others.

The Ti-6Al-4V alloy also displayed the same type of thickness dependency of toughness parameters as the two aluminum alloys, Fig. 5a and b. For this alloy none of the specimens satisfied the ASTM thickness requirement. For J_{Ic} testing the minimum thickness of $50J_{Ic}/\sigma_{ys}$ was approximately 0.35 in. when the maximum load was used as the critical point. However, constancy of J_{Ic} was not observed for any of these tests. Even when the onset of subcritical crack growth was selected as the critical point, \bar{G}_{Ic} , \tilde{G}_{Ic} and J_{Ic} showed small increases with decreasing thickness. The onset of subcritical crack growth was less well defined for this alloy and hence the accuracy of determination of this point was lower than for the aluminum alloys.

It has been shown that in all three alloys the G_{COD} values were very large and irregularly varying with thickness as compared to the other three toughness parameters. Probably this is because, in addition to the large approximations made in the development of the COD method, a suitable technique for determining COD in compact tension specimen does not exist. All suggested techniques, including the one used in this investigation, are quite sensitive to subcritical crack growth, which tends to yield unreasonably large values of COD.

The differences in \tilde{G}_{Ic} and J_{Ic} from \bar{G}_{Ic} were large when the peak load was taken as the critical point. When the onset of subcritical crack growth was taken as the critical point, there were no large differences among the three toughness values, and \bar{G}_{Ic} was almost the same as the ASTM standard toughness (G_{Ic}) value. This behavior indicates that in all three alloys the nonlinearity occurred predominantly after the onset of subcritical crack growth. It also indicates that valid G_{Ic} values can be obtained from specimens of thickness much less than that required by ASTM E399 by evaluating \bar{G}_{Ic} at the onset of subcritical crack growth. This can potentially lead to elimination of the need for large unwieldy test specimens and result in significant savings in materials and testing expenses.

Comparison of either the \tilde{G}_{Ic} or J_{Ic} toughness values at the two critical points illustrates quite clearly the severe penalty paid by evaluating fracture toughness values only at the onset of subcritical crack growth. For example, the \tilde{G}_{Ic} values evaluated at the maximum load are generally two to three times as large as the values obtained at the onset of subcritical cracking. Since the prevention of unstable fracture of engineering structures is the primary application of fracture mechanics, it is important to incorporate the complete material response (load-displacement record) into the fracture toughness determination.

CONCLUSIONS

1. Comparisons among \bar{G}_{Ic} , \tilde{G}_{Ic} , J_{Ic} and G_{COD} were made for three alloys. The toughness values were evaluated at maximum load and at the onset of subcritical crack growth.
2. When the maximum load was taken as the critical point, all of the toughness parameters displayed higher values with decreasing specimen thickness. When the onset of subcritical crack growth was taken as the critical point, \bar{G}_{Ic} , \tilde{G}_{Ic} and J_{Ic} were essentially constant at all thicknesses. In both cases G_{COD} had higher values than the other three and varied irregularly with thickness.
3. \tilde{G}_{Ic} and J_{Ic} varied in a similar fashion, with \tilde{G}_{Ic} always greater than J_{Ic} whenever significant nonlinearity occurred. At the onset of subcritical crack growth and for brittle fracture, \tilde{G}_{Ic} , J_{Ic} and \bar{G}_{Ic} gave generally similar toughness values with J_{Ic} often lower than \tilde{G}_{Ic} and \bar{G}_{Ic} .
4. When the toughness values were determined at the onset of subcritical crack growth they remained constant down to much lower thicknesses than those required by the ASTM standard. Most of the nonlinearity occurred after the onset of subcritical crack growth.

5. Minimum thickness requirements by ASTM E399 and by J_{Ic} criterion have been evaluated and it was seen that the E399 requirement was an order of magnitude greater than J_{Ic} . However J_{Ic} values were not constant below the ASTM required thickness when J_{Ic} was determined at the maximum load. A thickness of $50 J_{Ic} / \sigma_{ys}$ is not adequate to provide constancy of toughness values at maximum load.

6. Constancy of J_{Ic} and \tilde{G}_{Ic} with thickness were very similar for all of the tests.

7. The test results indicate that valid G_{Ic} values can be obtained from specimens of thickness much lower than that required by ASTM E399 by evaluating \tilde{G}_{Ic} at the onset of subcritical crack growth.

8. Comparison of \tilde{G}_{Ic} or J_{Ic} at the two critical points illustrates the severe penalty paid by evaluating fracture toughness values only at the onset of subcritical crack growth, since \tilde{G}_{Ic} values at maximum load were generally two or three times as large as the values at the onset of subcritical cracking.

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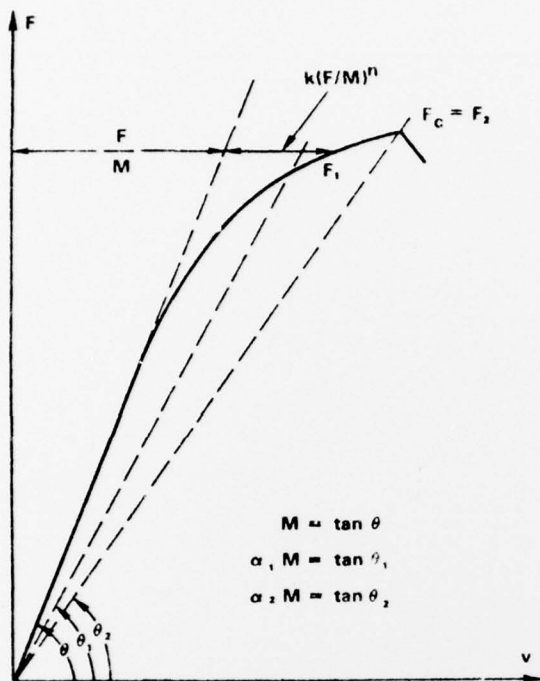


FIG. 1. TYPICAL NONLINEAR LOAD-DISPLACEMENT CURVE SHOWING THREE-PARAMETER REPRESENTATION AND REDUCED MODULUS LINES

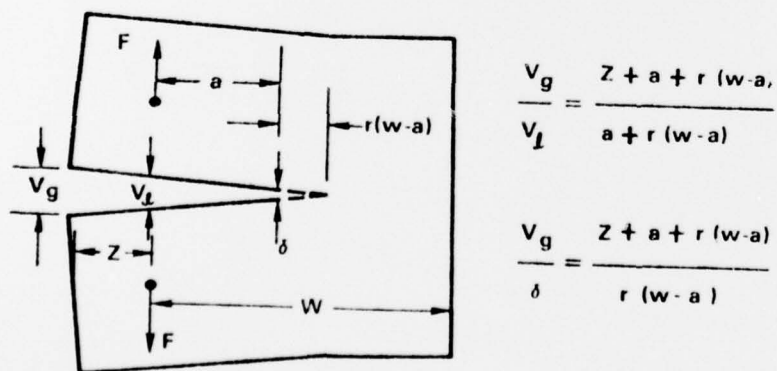


FIG. 2. A MODEL FOR DETERMINING DISPLACEMENT ALONG LOADING LINE AND AT THE CRACK TIP.

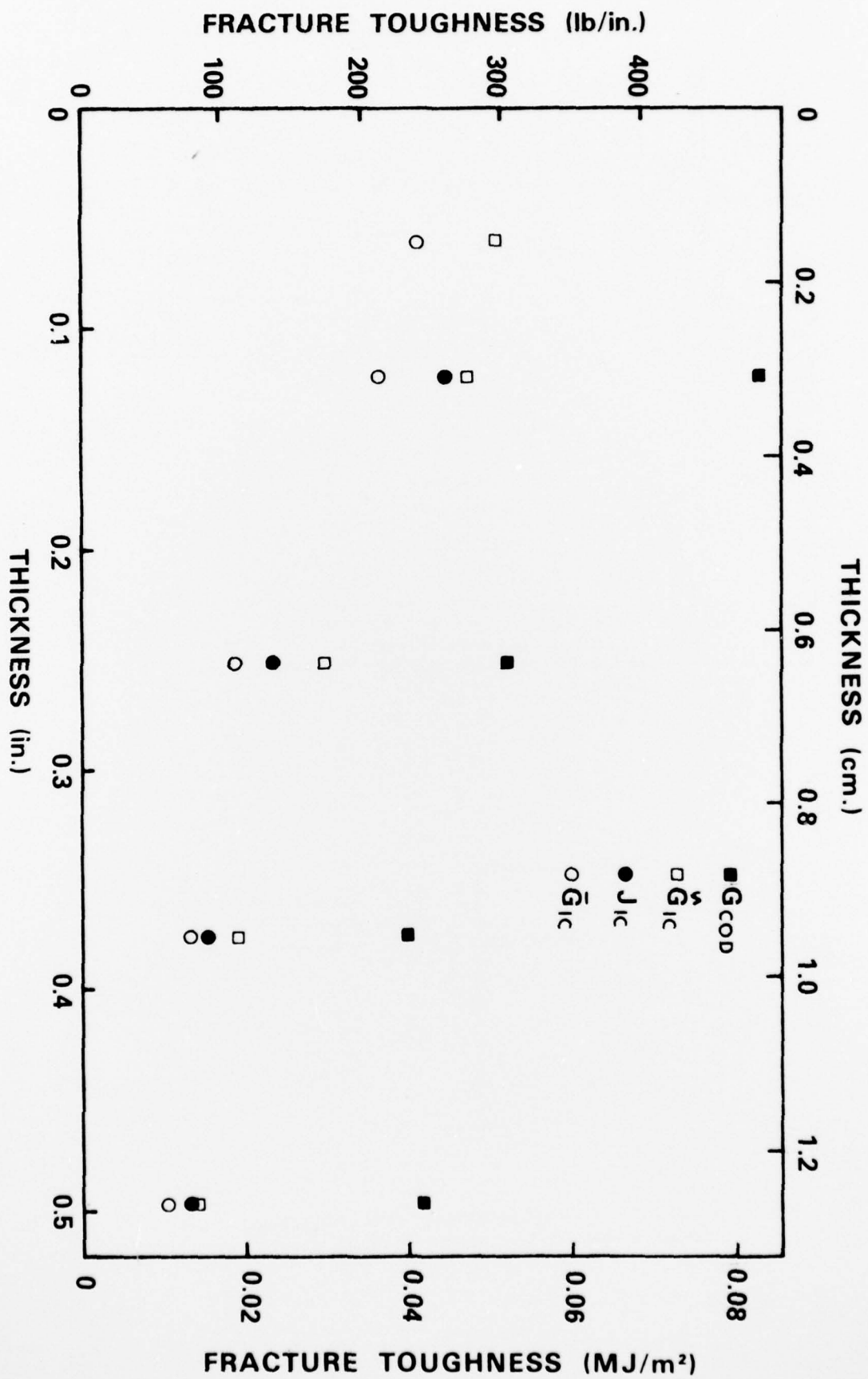


Fig. 3a. Variation of toughness parameters with specimen thickness for 7075-T651 (L-T), determined at peak load.

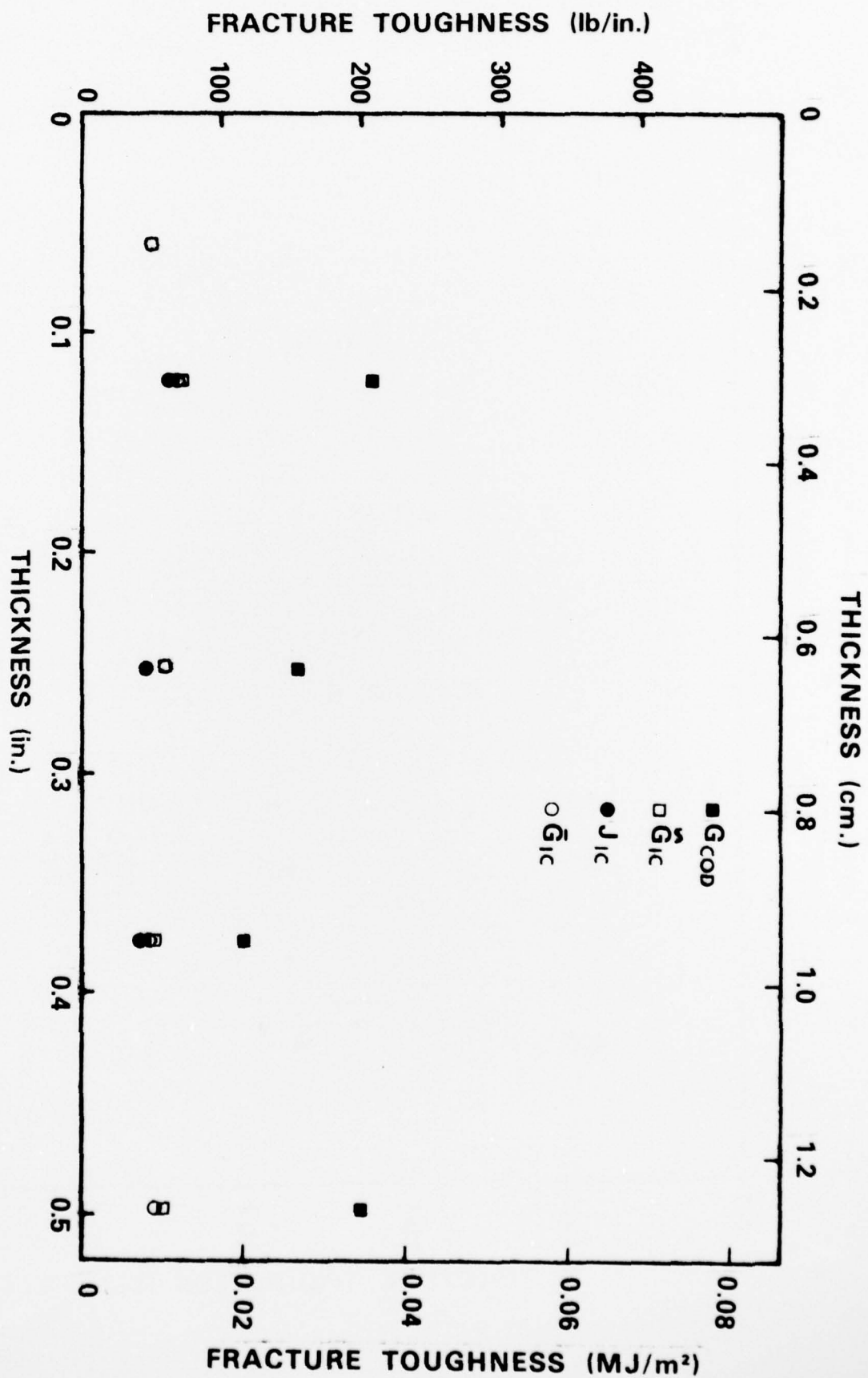


Fig. 3b. Variation of toughness parameters with specimen thickness for 7075-T651 (L-T), determined at the initiation of subcritical crack growth.

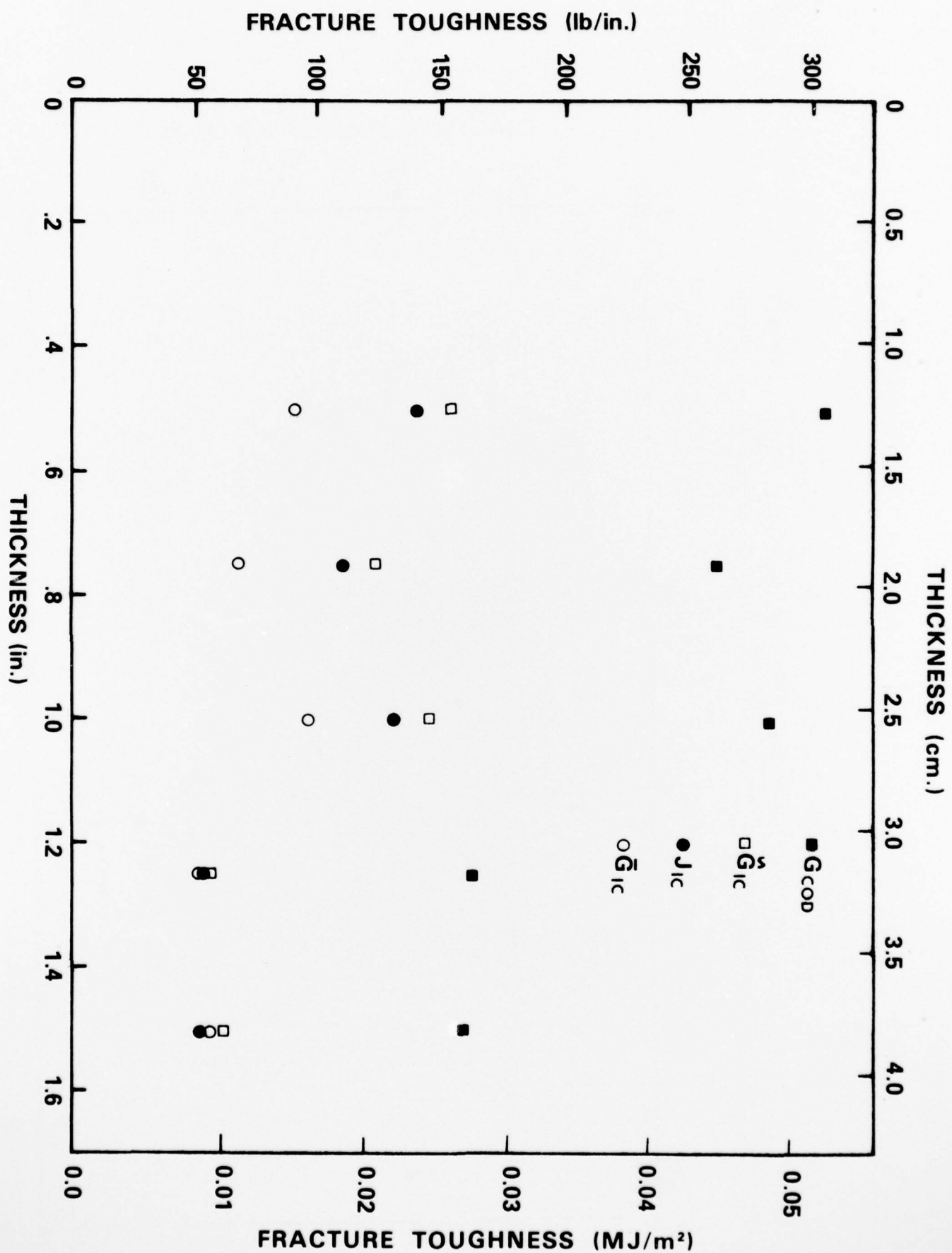


Fig. 4a Variation of toughness parameters with specimen thickness for 2124-T851 (T-L), determined at peak load.

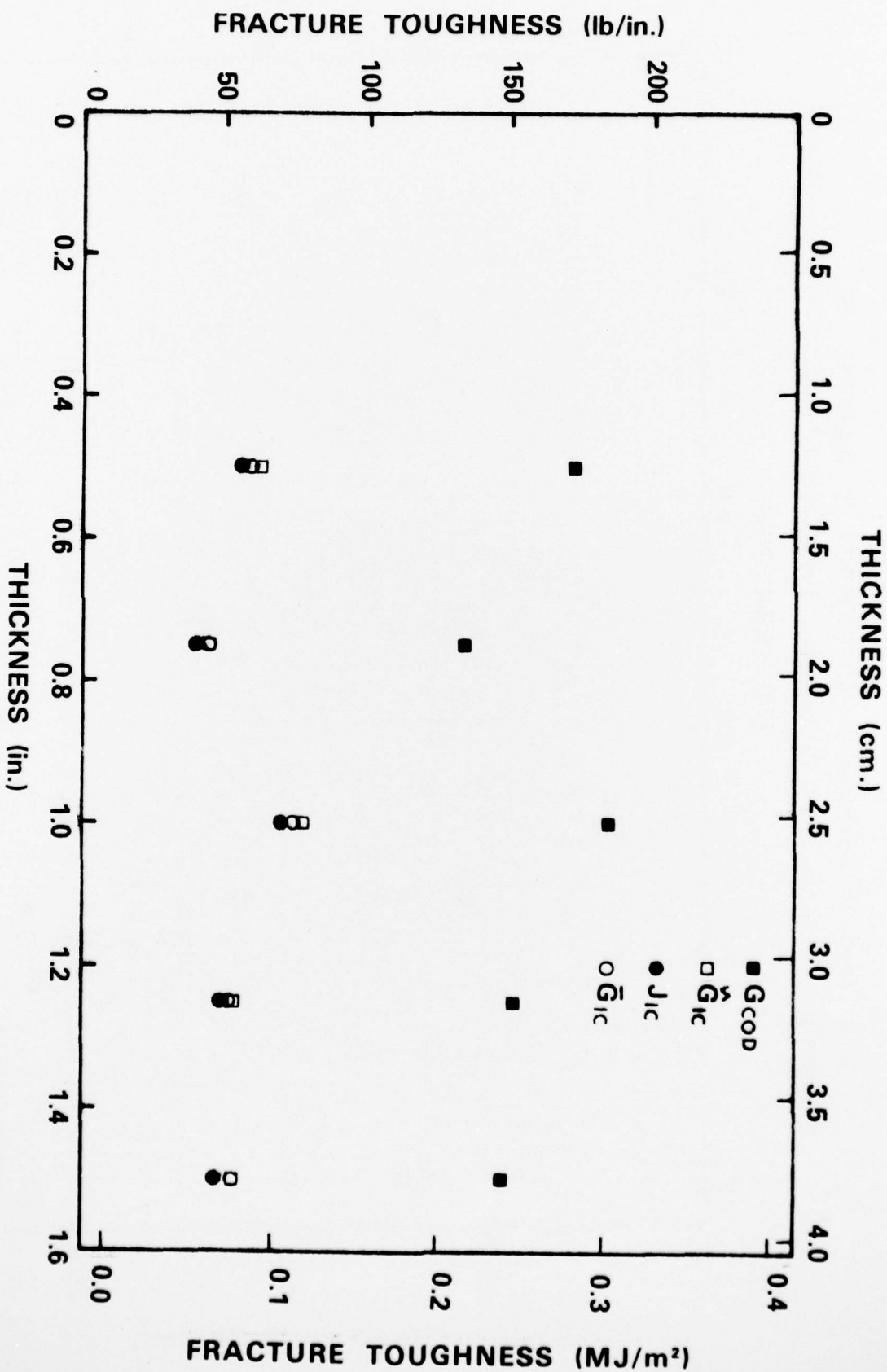


Fig. 4b Variation of toughness parameters with specimen thickness for 2124-T851(T-L), determined at the initiation of subcritical crack growth.

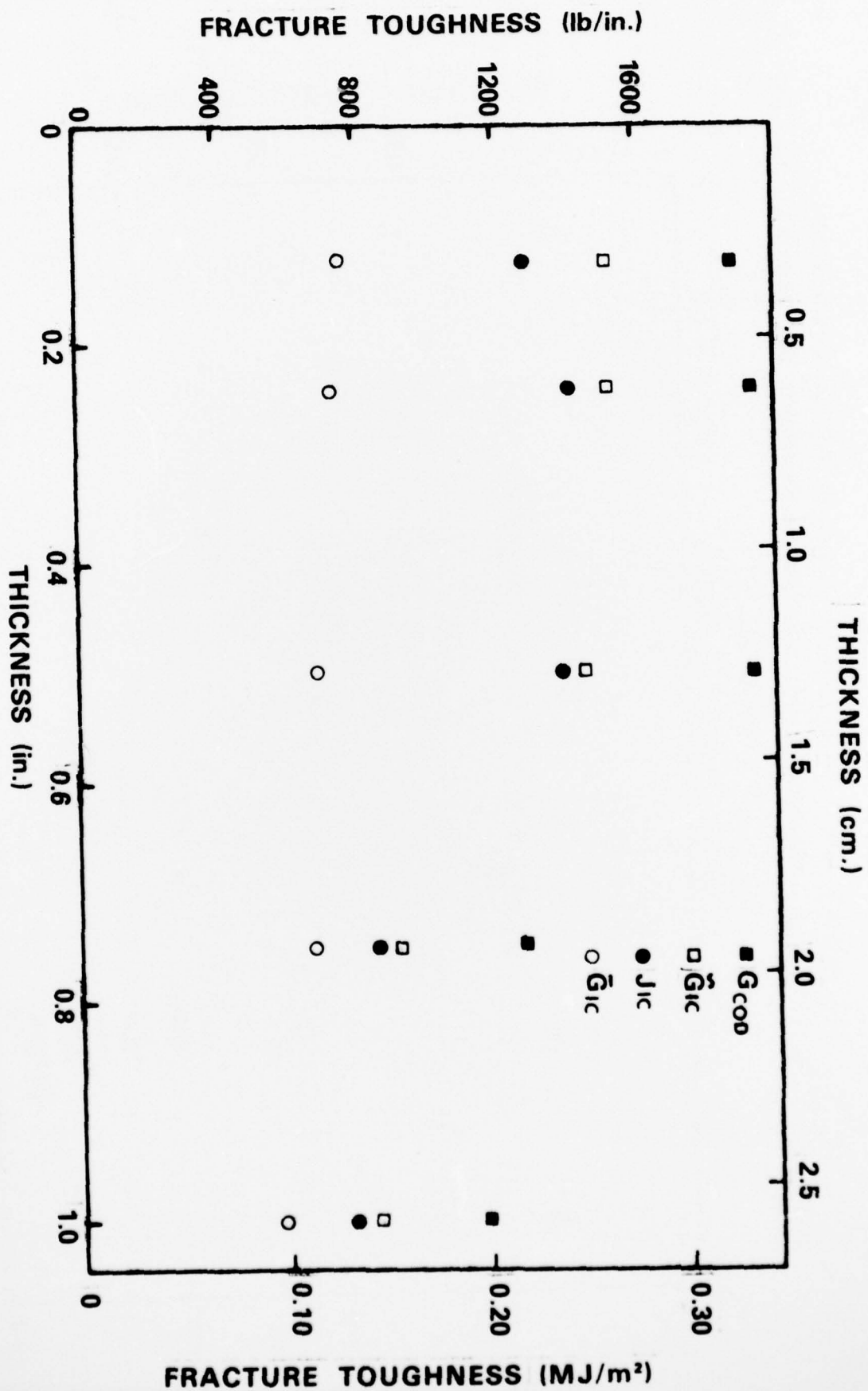


Fig. 5a. Variation of toughness parameters with specimen thickness for Ti-6Al-4V, β forged (L-T), determined at peak load.

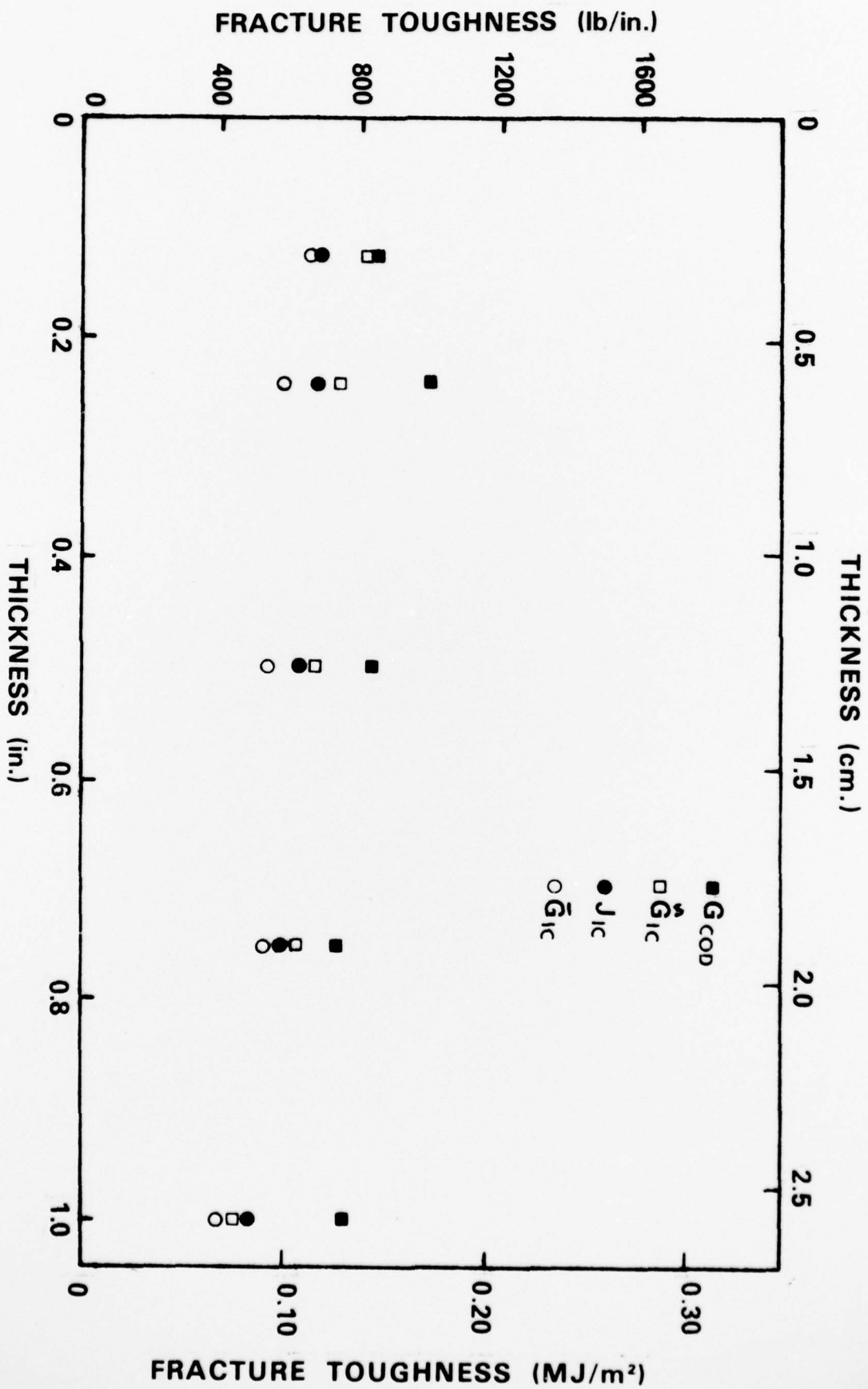


Fig. 5b. Variation of toughness parameters with specimen thickness for Ti-6Al-4V, β forged (L-T), determined at the initiation of subcritical crack growth.

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20. ABSTRACT (Continue on reverse side if necessary and identify by block number) Theoretical and experimental comparisons have been made between several nonlinear fracture toughness methods including J _{Ic} (J integral method), G _{CO_D} ^{↑↑↑} (COD method) and G _{Ic} (nonlinear energy method). Three series of compact tension specimens of 7075-T651, 2124-T851 and Ti-6Al-4V were tested. Five fracture toughness tests, at thicknesses above and below the minimum value for plane strain fracture, were conducted in each series, and toughness		

cont → values were compared at: (a) the onset of stable crack growth and (b) at the onset of unstable fracture. It was found that when the critical point was the onset of stable crack growth $J_{Ic}^{\uparrow\uparrow}$, G_{Ic} and \bar{G}_{Ic} (linear toughness) were independent of specimen thickness. When the critical point was the onset of unstable fracture all three toughness values increased with decreasing thickness, with $G_{Ic} > J_{Ic}^{\uparrow\uparrow} > \bar{G}_{Ic}$. The $G_{COD}^{\uparrow\uparrow\uparrow}$ values were much higher than the others in all cases.



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